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VARIABLES AFFECTING THE PERFORMANCE
OF A FOG-TYPE DUST COLLECTOR

A THESIS

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the Faculty of the Graduate Division

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VARIABLES AFFECTING THE PERFORMANCE

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SUMMARY

A fog-type dust collector utilizes principles of the cyclone as well as those of spray scrubbers. The construction is such that water sprayed into the chamber can induce quantitites of air in a spiral path. Due to impaction and centrifugal effects water drops (and solids) are removed from the gas stream which reaches a high degree of saturation with water vapor depending upon operating conditions.

This investigation was conducted to study (1) the effect of spray-pressure water flow rate and air volume on moisture carryover, and (2) the effect of spray pressure and water flow rate on induced air flow. Moisture carryover is not a problem exclusive to the fog-filter but is peculiar to almost all of the wet type cleaners including dynamic types as well as packed towers, air washers, and wet filters.

A fog-filter of given geometry was set up for the test with necessary pumps, thermometers, and fan to determine the specific humidity of air. Wet and dry bulb thermometer readings were recorded at entry and exit points and the dew point temperature of air leaving the spray was also recorded.

For the induced air flow phase of the test, spray pressure and water flow rate were varied. Runs lasted for ten minutes during which three readings were taken and averaged. For the moisture carryover test, air flow, spray pressure, and water flow rate were varied. The same timing was used.

Air flow increased with pressure and water flow rate, reaching a

maximum for the given geometry of 214 cu. ft/min at a spray pressure of 600 psig and a water flow rate of 2.37 cu. ft/min. Water flow was found to vary according to

$$Q = KNP^n$$

where Q = nozzle bank water flow rate cu. ft/min

K = dimensional constant = 0.0114

n = pressure exponent = 0.631

P = pressure (psig)

N = number of nozzle banks in operation.

Moisture carryover was found to vary with pressure and air flow in the following manner:

$$CO = xP^m$$

where x and m are functions that vary with air flow

CO = carryover lb. moisture/lb. air

P = pressure (psig).

Entrainment seemed to be independent of the number of banks operating, as one single curve represents the trend of the data for four banks as well as for one bank. The entrainment results would be more valuable if there were available data for comparison of the entrainment with the efficiency of the fog filter at the same operating conditions.

It is recommended that a study of the efficiency of the fog filter be made at low, medium, and high dust loads. An investigation of the fog filter as a packaged cooling tower should also be made.

CHAPTER I

INTRODUCTION

The fog-type air cleaner of the type used in this investigation is manufactured by the Saran Lined Pipe Company and the R. C. Mahone Company under the trade names "Fogitron" and "Fog Filter." Other fog devices are being manufactured which differ in geometry and method of atomizing the water.

This device, hereafter called the fog-clone in deference to the trade names, utilizes principles of the cyclone as well as those of spray scrubbers. The construction is such that water sprayed into the chamber can induce quantities of air in a spiral path. Due to impaction and centrifugal effects, water drops (and solids) are removed from the gas stream which reaches a high degree of saturation with water vapor depending upon operating conditions.

By placing a number of banks of nozzles inside a round vertical tower and pointing them horizontally in the same angular direction, the combined effect is to rotate all of the air mass in the tower about its axis and at high angular velocity. The resulting centrifugal force causes particles large enough to be effected by it to be thrown to the wall of the tower. At the wall these particles become part of the liquid effluent draining to the base cone, from which the effluent is pumped to a recirculating tank or sump. The force of the high pressure spray particles impinging upon the chamber wall continuously sccurs it and prevents caking of solids on tower walls.[1]

The Problem.--The purpose of this investigation was to study the effect of spray pressure and water flow rate on induced air flow and the effect of spray pressure, water flow rate and air flow on moisture carryover and moisture entrainment in the fog-clone. For a clear definition of the terms used herein you are referred to the Glossary in Appendix C.

Except for rather incomplete data on efficiencies of the fog-clone in removing particular air contaminants, little is known about the effect of geometry on its performance. Even for a given geometry the literature does not give the effect of air flow rate, water pressure and water flow rate on moisture entrainment nor the effect of water pressure and flow rate on induced air flow.

Moisture carryover is not a problem exclusive to the fog-clone but is peculiar to almost all of the wet type cleaners including dynamic types as well as packed towers, air washers, and wet filters.

Objective.--The objective of this investigation is two fold. First, it is desired to explain the "pumping action" of the water spray in terms of its pressure and volumetric flow rate. Second, the prediction of moisture entrainment in terms of the three principal variables--air and water flow and water pressure--is sought.

The achievement of these objectives may well permit (1) evaluation of the fog-clone as a cooling tower and (2) reasonable estimates as to effluent air pollution, rainout, makeup water and prediction of ultimate capacity.

Previous Work.--Kernan[2] in 1952 submitted at the Georgia Institute of Technology a thesis on the fog-type dust collector. He studied the collection efficiency of the collector for low concentrations of kaolin dust but because of equipment failure his data is limited. Thomas[3] presented a paper in 1952 on the effectiveness of the fog filter as an air cleaner. Neither of these two analyses provided information on induced draft or moisture entrainment in the air discharged. A literature search made by Kernan and Thomas showed that there is little published on moisture carryover and moisture entrainment from a scrubber of this type. Kropp[4] used a fog filter of the same design to control hydrogen sulfide and fatty acid odors. Here again the object is evaluation of the unit as an air cleaner. He found the filter to be more efficient at a fume rate of 800 to 1000 cu. ft/min with a water rate of 20 gal/min at 400 psig. He also used scrubbing liquids such as soda ash, recycled water and caustic soda. He does not mention entrainment or carryover of the scrubbing medium.

CHAPTER II

APPARATUS

The Air System.--The apparatus used by Kernan served as the basic equipment for this investigation although a number of modifications and some additional equipment were necessary to make the apparatus meet new requirements. Figure 1 and Figure 2 show the general layout of the equipment.

Air is induced into the system by a Buffalo Forge Company paddle-wheel type fan through a 90 degree elbow and 27 diameters of horizontal eight inch duct. The moisture laden air emerging from the spray entered a fin type unit heater after passing through two diameters of vertical duct and a 90 degree elbow. After leaving the unit heater, the air passes through 15 diameters of horizontal eight inch duct, a 90 degree elbow and four diameters of vertical eight inch duct into the fan from which it is discharged to the atmosphere.

The Water System.--A John Bean Triplex Pump supplied the water to the nozzle banks. Since the pump discharged a constant volume of water, spray pressure is controlled by a spring loaded by pass relief valve. An air chamber is used to absorb pressure surges of the pump. A Gould centrifugal pump is used to move the water from the fog-clone cone to the recirculation tank (hereafter called the reservoir) located under the high pressure pump. City water is also piped to the reservoir in order to provide makeup water and supply the initial volume of water.

A small gear-type feed water pump attached to the reservoir is used for emptying when necessary. Water was recirculated throughout the test described here.

The Fog-clone.--The fog-clone is of sheet metal construction with diameter of three feet and height of four feet. Five rows of six nozzles each are spaced throughout the height of the fog-clone in parallel horizontal planes. These discharge at a common angle of approximately 45 degrees from the radius toward the center of the tower concurrent with rotation of air in the chamber. John Bean number 2-1/2 hard center nozzles are used. A gate valve for each bank of nozzles provides shut-off control of the water flow to the nozzles.

The eight inch diameter air entrance duct was arranged tangential to the outer casing at the top of the fog-clone and at a downward angle of approximately 30 degrees from the horizontal. The eight inch diameter air discharge duct was arranged concentric to the outer casing and extended down into the collector for a distance of 40 inches ending in a bell-shaped opening.

A conical funnel (called the cone) is attached to the base of the fog-clone with metal screws and sealed against air and water leaks. The water flows from the cone into the circulating pump.

Instrumentation.--A thin plate orifice made and calibrated by Thomas[5] was checked and found to comply with the ASME fluid meters report.[6] This orifice is located on the intake side of the collector 17 diameters from the intake and 10 diameters from the fog-clone. Four flange taps located around the periphery of the duct on each side of the orifice are connected to a common tube. These flange taps as well as the location of the orifice conform with ASME specifications.[7]

The wet and dry bulb method is the most widely used today to determine the state of air and water vapor mixtures. Errors in temperature vary from one to ten percent depending on air movement and radiation.[8] Wet bulb methods are acceptable in air conditioning work and are easily adapted to almost any situation.

Wet bulb thermometers are placed at the entrance of the intake duct and before the 90 degree elbow on the discharge side. A standard thermometer is placed in the duct just above the collector but well below the center line of the heater to cut down the effect of radiation. The temperature after the spray is taken as the dew point temperature. The temperature of spray water is taken in the reservoir from a thermometer suspended in it.

An alcohol micromanometer is connected across the orifice to measure air flow and a by pass system consisting of two eight inch diameter positive shut-off slide dampers were used to regulate the air flow through the fog-clone.

A commercial water meter is placed between the centrifugal pump and the reservoir to measure the water flow. A bourdon pressure gauge with a range of zero to 800 pounds per square inch is installed on the nozzle bank manifold.

Heater.--Since the air leaving the fog-clone is suspected of containing entrained moisture it is necessary to provide some means for determining the magnitude of the entrainment. Several means were considered among which were chemical absorption, regrigeration, and reheating. The last method was selected since it required less equipment and appeared to be more accurate for this test. A unit heater supplied with low pressure steam was selected to heat the air.

The unit heater in the line increased the air temperature enough to evaporate the entrained moisture and give a measurable wet bulb depression. The heater is placed adjacent to the fog-clone just after the 90 degree elbow in the discharge line. The heater steam is obtained from the building heating supply.

Miscellaneous Equipment.--A barometer, stop watch and several thermometers are used in conducting the test.

CHAPTER III

PROCEDURE

Induced Air Test.--Water flow rate is a function of spray pressure and the number of banks in operation. During the tests spray pressure was varied from 100 psig to 600 psig at 100 psig intervals. The apparatus is the same as used in the moisture carryover test, with the exception that the discharge duct and heater are removed.

The high pressure pump is started with all four nozzle banks open. Next the centrifugal circulating pump is started. Wet and dry bulb thermometers are placed at the intake and discharge side of the fog-clone. The alcohol micromanometer is set up to read the pressure drop across the orifice. A thermometer is placed in the reservoir to record spray temperature. The relief valve on the high pressure pump is adjusted so as to obtain the desired spray pressure. Sufficient time is allowed for the temperature to reach equilibrium. The stop watch is started simultaneously with the reading of the water meter. The pressure drop across the orifice is recorded and all thermometers are read. At the end of five minutes and again at ten minutes all readings are repeated and recorded. This procedure is repeated at the same pressure with three, two and one nozzle bank in operation. Then the pressure is increased 50 pounds and the process repeated.

Moisture Carryover.--The equipment is arranged as described in Chapter 2. Air flow, water flow, and water pressure are varied in this phase of the test. Air flow ranged from 200-800 cubic feet per minute. Water pressure from 100-600 pounds per square inch gauge and water flow varied from 0.28-2.37 cubic feet per minute by operating one to four banks at various spray pressures.

The sequence of setting up the test is as follows: Steam is turned on for the heater, high pressure pump started, fan turned on, and circulating pump started. The two way damper is regulated to obtain the desired air flow. Next the high pressure pump relief valve is regulated to obtain desired pressure. Time is allowed for thermometers to reach equilibrium. The stop watch is started as the water meter is read. Spray pressure and air flow are held constant as the nozzle banks are varied from one to four. Runs last ten minutes with readings taken at zero, five and ten minutes. After this pressure is held constant, air flow increased, and the above repeated. This procedure is continued until the entire range is covered. Temperatures of air in, air after spray, air out, and spray water temperature are taken, the water flow recorded and the barometer read. Now pressure was increased to the next range and the cycle repeated.

CHAPTER IV

DISCUSSION OF RESULTS

Induced Air Flow.--The effect of spray pressure on induced air flow is shown in Figure 4. All curves follow the same general trend. Water flow depends on spray pressure as well as number of nozzle banks in operation. As spray pressure is increased water flow increases. The equation governing water flow was written

$$Q = KNP^n$$

where Q = bank flow in cu. ft/min

K = dimensional constant = 0.0114

N = number of banks

P = nozzle pressure

n = pressure exponent = 0.631.

The appearance of N is due to the fact that there are six nozzles on each bank, and an increase from one bank to two banks doubles the water flow rate, etc. The curve for one nozzle bank, Figure 3, was plotted by taking the water flow rate four four, three and two nozzle banks and dividing by four, three and two, respectively. The results were then plotted along with the water flow rate for one bank and the curve fitted to the data. The induced air flow increases as expected, that is, the higher the velocity of spray (this increased with the n^{th} root of the pressure where $n = 1/2$) and the greater the flow of water, the more induced air. The curves seem to flatten out around 600 psig, probably due to

(1) Drop size becoming smaller, hence drag per particle diminishes, although the total number of drops increases.

(2) Mean velocity difference between drop and air stream diminishes rapidly with decreasing drop size.

Moisture Carryover.--Moisture carryover was found to vary with air flow and spray pressure according to the following equation:

$$CO = xP^m$$

where CO = carryover $\frac{\text{lb. moisture}}{\text{lb. air}}$

x = coefficient for a given air flow

P = spray pressure (psig)

m = pressure exponent for a given air flow.

The variation of x and m are given below:

Air Flow Cu.Ft/Min	200	300	400	500	600	700
x	0.0034	0.0075	0.0895	0.0403	0.0366	0.0012
m	+0.255	+0.111	-0.327	-0.221	-0.228	+0.321

No single equation was obtained to relate air flow, water flow and spray pressure to moisture carryover. Moisture content of entering air will definitely have an effect on carryover.

Moisture Entrainment.--The results of the entrainment evaluation are given in Table 3. No means of correlating this data was found, but Figure 5 and Figure 6 are curves of Entrainment vs Air Flow at 400 and

500 psig, respectively. As stated previously the number of nozzle banks does not have an appreciable effect on entrainment, so the curves shown are trends rather than point-to-point curves.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions.--The lack of available data for comparison leaves only one alternative, that is, to draw conclusions from the results of the tests alone. It must also be realized that geometry influences this problem, just how much is beyond the scope of this thesis.

The conclusion can be drawn from the air flow curves that with four and three banks in operation the induced air flow takes a sharp increase at 300 psig and seems to level out at the maximum peak of 214 cu. ft/min. This peak was reached at a spray pressure of 600 psig and a water flow rate of 2.37 cu. ft/min. At higher pressures (greater than 300) there was not an appreciable difference between one bank and two banks whereas the difference between two, three and four banks was noticeable. This leads to the conclusion that the greater number of nozzle banks the greater the induced air flow. This would no doubt reach a maximum, but just where has not been determined.

It can be concluded that entrainment at the higher air flows is high for low pressures, but reaches a minimum at 400 psig, and then rises again. Entrainment at low air flows seems to be fairly independent of spray pressure. Figure 5 and Figure 6 show that entrainment is almost independent of water flow rate, or rather number of nozzle banks in operation. A trend curve plotted for a test pressure of 400 and 500 psig revealed that all points are very close together for any number of nozzle banks used.

Water loss from carryover can be determined by the equations included in the discussion of results. This may be important in cooling tower considerations where the determination of the amount of makeup water for the fog-clone may be required.

Recommendations.--There are many variables that affect the performance of the fog-clone. Here we have investigated induces air flow, carryover, and entrainment. For the best evaluation of the data contained herein, investigation should be given to a study of the efficiency of the fog-clone at the same operating conditions; further, a comparison with the carryover and entrainment would be in order. This work was done in the moderate pressure and air flow range; higher air flows and pressures are yet to be investigated. Geometry, location of banks, size and design of nozzles, and air flow path were fixed for this test. Perhaps these items should be investigated before any set characteristics can be tabulated as to factors that control the design of fog-clones. Before the fog-clone can be successfully engineered to the job, more information needs to be formulated.

The practicability of the fog-clone as a packaged cooling tower should also be investigated.

APPENDIX A

ILLUSTRATIONS

Figure 1

1. Wet and dry bulb thermometer for discharge air
2. Fin-type steam heater
3. Thermometer for air after spray
4. High pressure water pump
5. Air intake
6. Fog-clone dust collector
7. Water meter
8. Fan
9. Centrifugal pump for circulating water
10. Valves for controling water flow

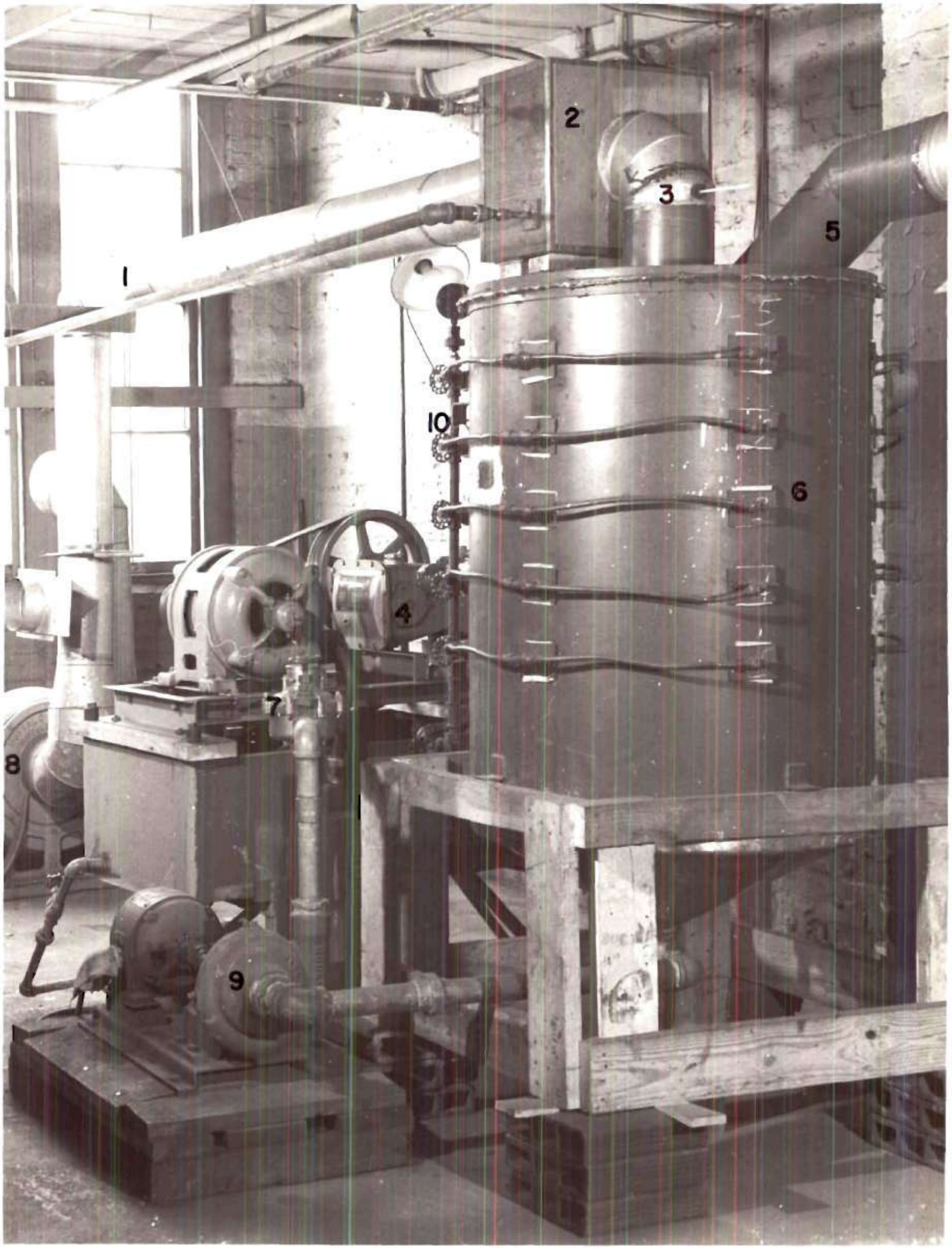

Fig. I. Photograph Of Apparatus For Test

Figure 2

1. Pressure gauge for nozzle spray
2. Air chamber
3. Pressure regulator
4. Reservoir for high pressure pump
5. High pressure pump
6. Thermometers for spray water

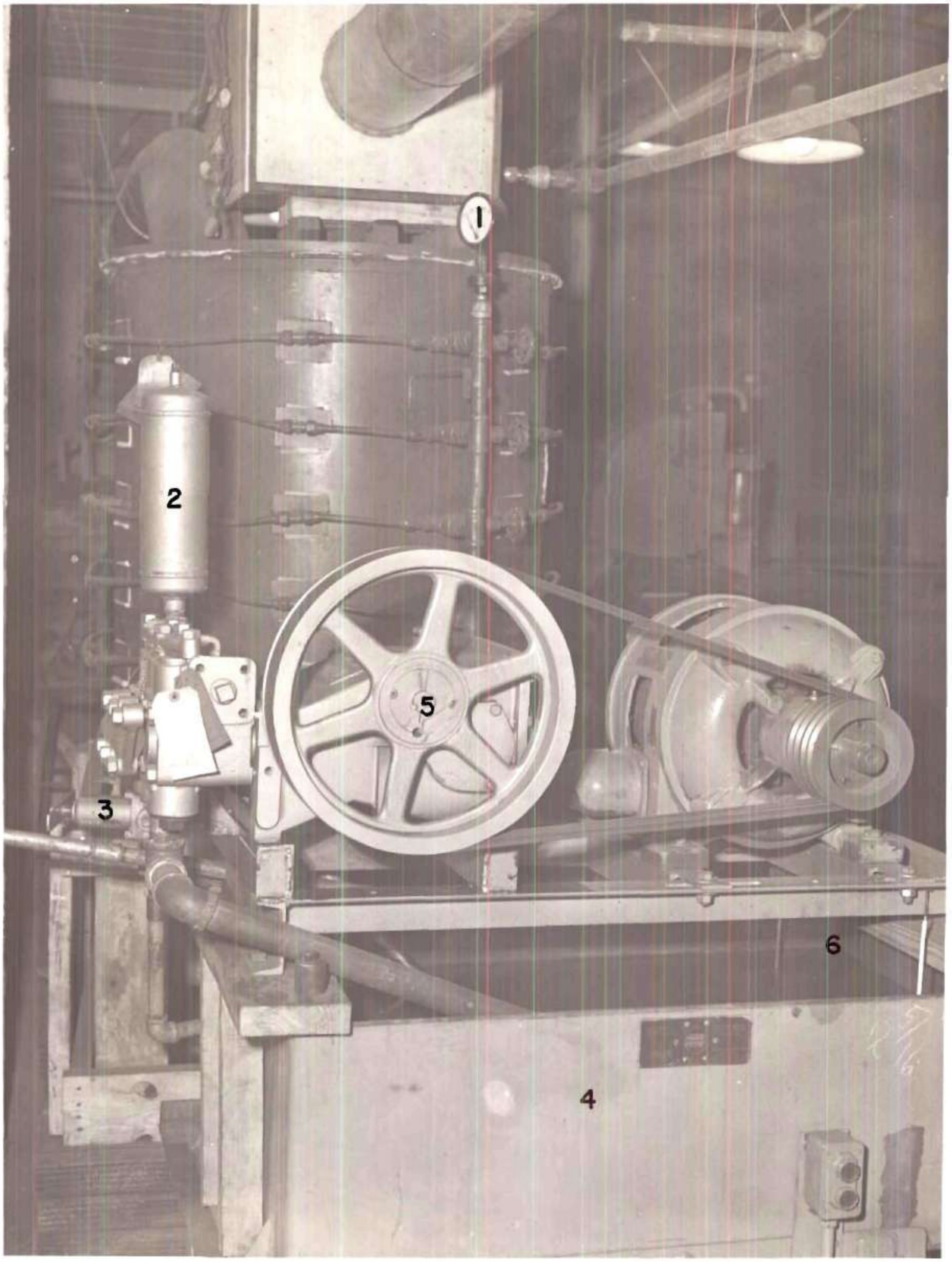

Fig. 2. Photograph Of High Pressure Pump

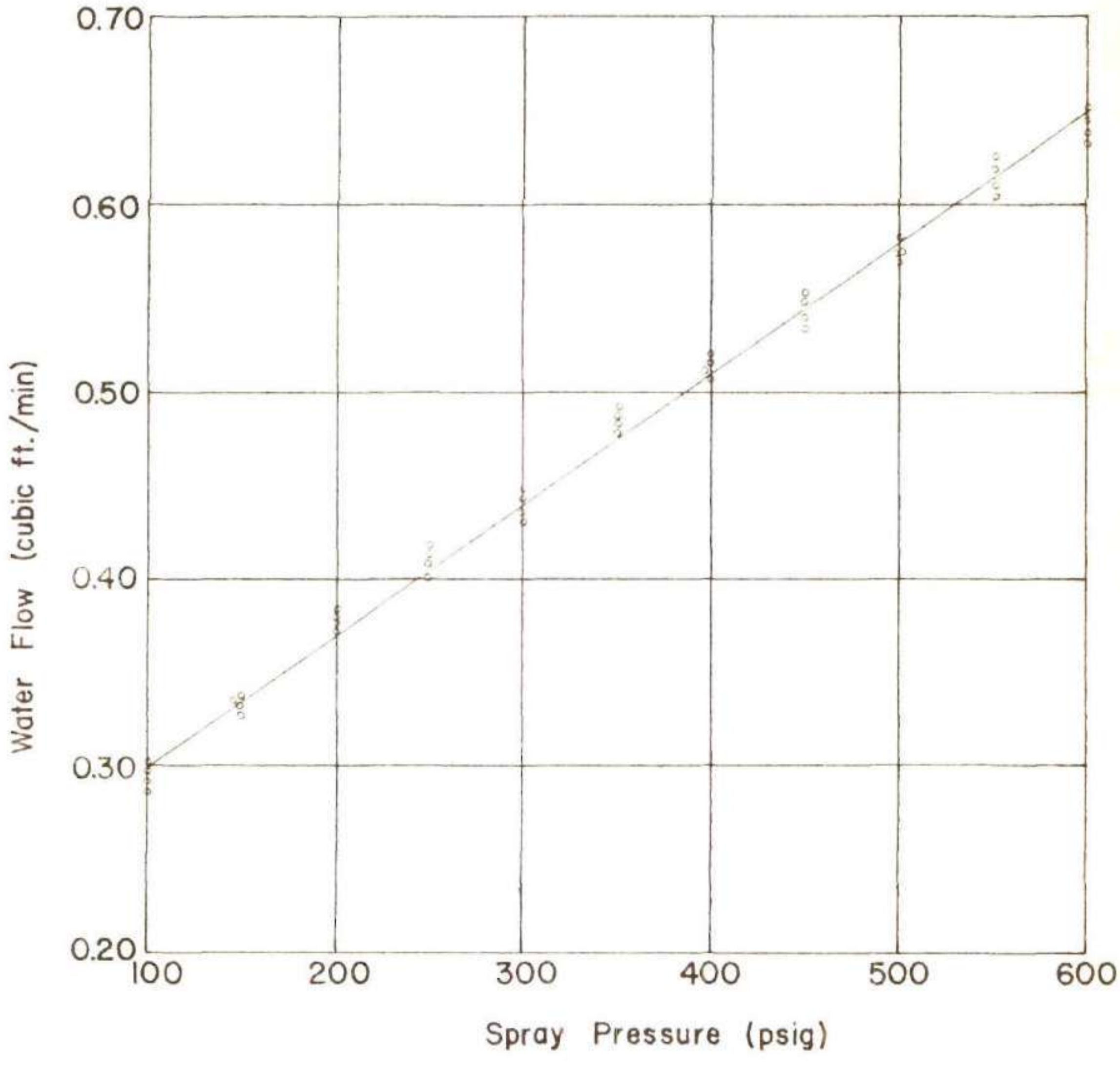

Figure 3

Water Flow Per Nozzle Bank

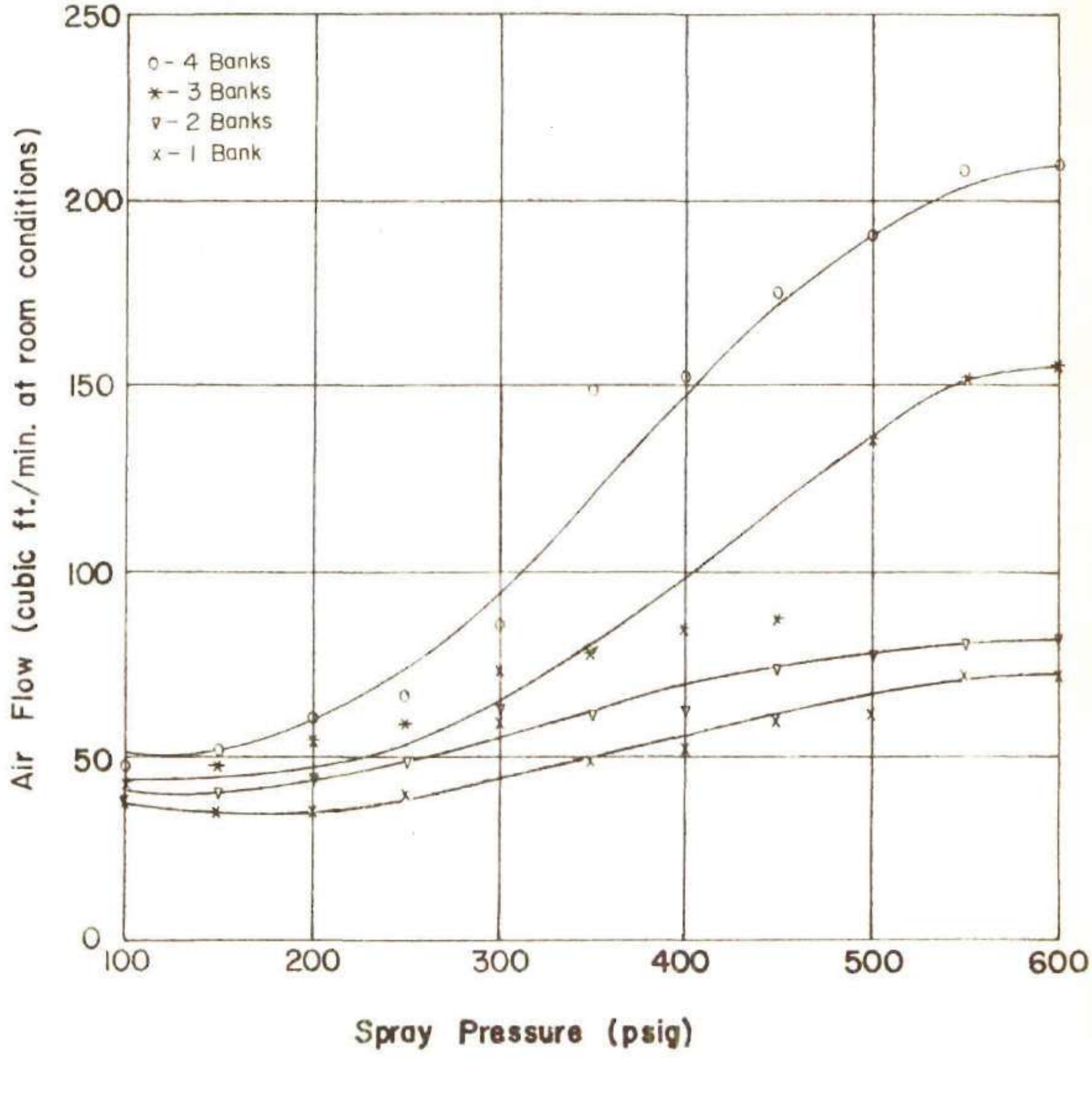

Figure 4

Induced Air Flow

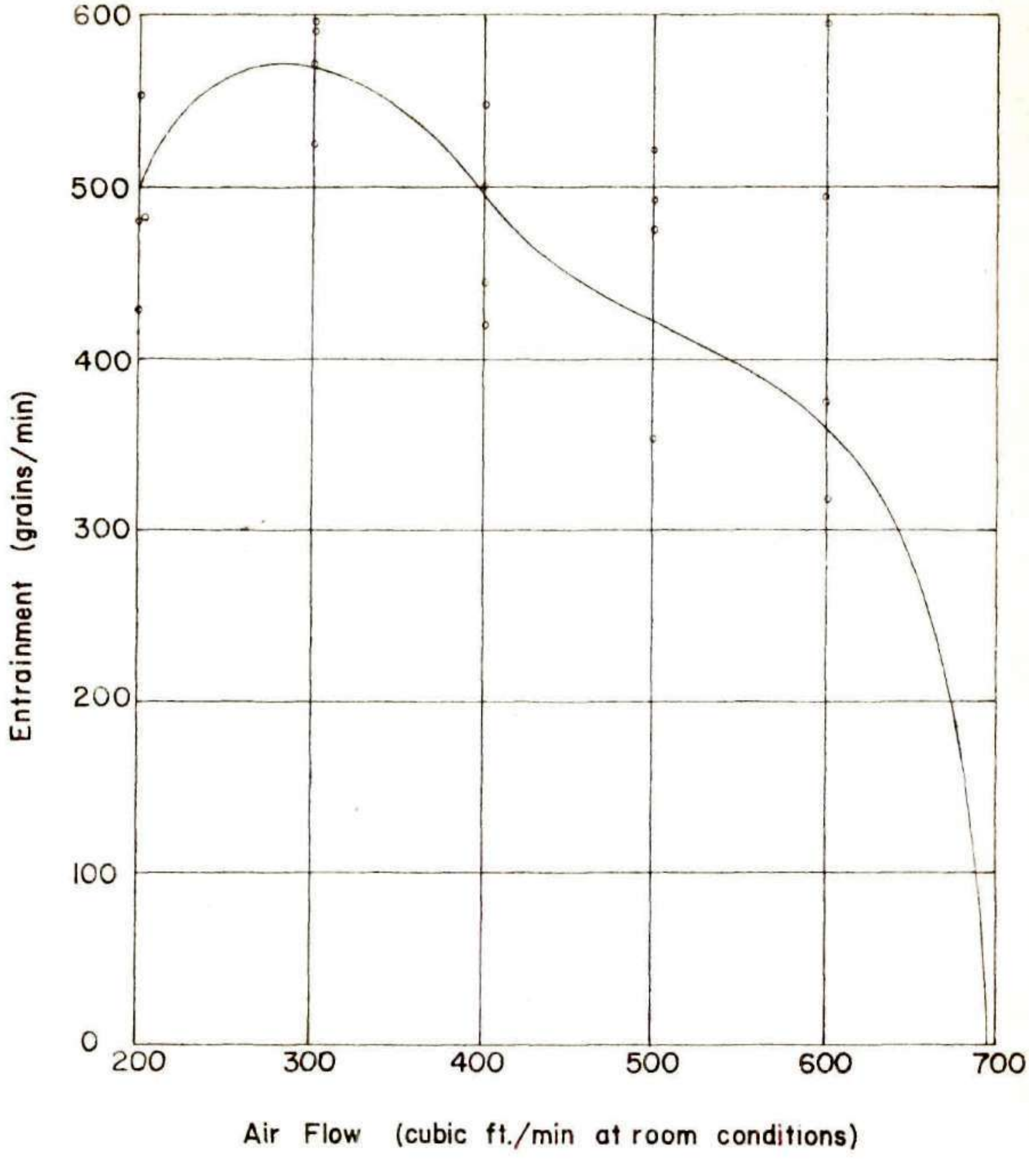

Figure 5

Entrainment At 400 psig

Figure 6

Entrainment At 500 psig

APPENDIX B

TABLES

Table 1. Experimental Data for Induced Air Flow

Number of Banks	Water Pressure psig	Water Flow Cu.Ft/Min	Air Flow Cu.Ft/Min	Barometer In. Hg.	Duration of Run Min
4	100	1.16	48	29.05	10
4	150	1.29	54	28.87	10
4	200	1.40	61	28.87	10
4	250	1.58	67	28.87	10
4	300	1.71	88	28.87	10
4	350	1.92	150	28.87	10
4	400	1.98	154	28.87	10
4	450	2.15	175	28.93	10
4	500	2.25	190	29.10	10
4	550	2.30	212	28.93	10
4	600	2.37	214	29.20	10
3	100	0.83	42	29.05	10
3	150	1.00	50	28.87	10
3	200	1.22	56	28.87	10
3	250	1.29	59	28.87	10
3	300	1.34	74	28.87	10
3	350	1.43	76	28.87	10
3	400	1.54	84	28.87	10
3	450	1.64	88	28.93	10
3	500	1.72	135	29.10	10
3	550	1.83	154	29.10	10
3	600	1.85	155	29.20	10
2	100	0.56	37	29.05	10
2	150	0.66	42	28.87	10
2	200	0.74	46	28.87	10
2	250	0.82	50	28.87	10
2	300	0.89	66	28.87	10
2	350	0.96	66	28.87	10
2	400	1.04	67	28.87	10
2	450	1.10	75	28.93	10
2	500	1.15	78	29.10	10
2	550	1.24	80	29.10	10
2	600	1.27	82	29.20	10

Table 1 (Contd.). Experimental Data for Induced Air Flow

Number of Banks	Water Pressure psig	Water Flow Cu.Ft/Min	Air Flow Cu.Ft/Min	Barometer In. Hg.	Duration of Run Min
1	100	0.28	37	29.05	10
1	150	0.34	37	28.87	10
1	200	0.39	37	28.87	10
1	250	0.40	42	28.87	10
1	300	0.45	61	28.87	10
1	350	0.49	50	28.87	10
1	400	0.52	51	28.87	10
1	450	0.54	61	28.93	10
1	500	0.57	62	29.10	10
1	550	0.61	74	29.10	10
1	600	0.72	74	29.20	10

Table 2. Experimental Data for Moisture Entrainment

Number of Banks	Water Pressure psig	Air Flow Cu.Ft/Min	Water Flow Cu.Ft/Min	Barometer In. Hg.	Air In t' °F	Air In t °F	Air After Spray °F	Air Out t' °F	Air Out t °F
4	100	200	1.20	29.08	50	63	62	84	126
4	100	300	1.22	29.08	52	65	62	90	120
4	100	400	1.21	29.08	52	66	61	89	114
4	100	500	1.21	29.08	55	70	61	86	109
4	100	600	1.22	29.08	54	69	60	83	105
4	100	700	1.14	29.22	52	69	57	72	101
4	100	800	1.17	29.15	56	76	61	73	102
3	100	200	0.96	29.08	51	64	62	87	126
3	100	300	0.96	29.08	52	65	62	89	119
3	100	400	0.93	29.08	52	66	60	89	113
3	100	500	0.92	29.08	55	70	61	86	109
3	100	600	1.01	29.08	54	69	59	83	105
3	100	700	0.94	29.22	52	68	56	72	100
3	100	800	0.89	29.15	56	76	61	73	102
2	100	200	0.63	29.08	51	64	62	88	126
2	100	300	0.62	29.08	52	64	61	88	119
2	100	400	0.62	29.08	53	67	60	89	113
2	100	500	0.62	29.08	55	71	62	86	110
2	100	600	0.59	29.08	54	68	58	82	104
2	100	700	0.62	29.22	52	68	56	71	100
2	100	800	0.59	29.15	56	76	61	72	102
1	100	200	0.32	29.08	51	64	62	89	127
1	100	300	0.32	29.08	51	64	59	85	118
1	100	400	0.31	29.08	54	68	59	89	112
1	100	500	0.31	29.08	55	71	60	85	110
1	100	600	0.31	29.08	54	68	58	82	104
1	100	700	0.30	29.22	52	68	56	70	100
1	100	800	0.28	29.15	56	76	62	72	102

Table 2 (Contd.). Experimental Data for Moisture Entrainment

Number of Banks	Water Pressure psig	Air Flow Cu.Ft/Min	Water Flow Cu.Ft/Min	Barometer In. Hg.	Air In t' °F	Air In t °F	Air After Spray °F	Air Out t' °F	Air Out t °F
4	200	200	1.45	29.22	58	72	69	88	129
4	200	300	1.43	29.22	56	69	66	82	120
4	200	400	1.47	29.14	53	66	62	87	115
4	200	500	1.47	29.14	50	62	60	82	108
4	200	600	1.46	29.08	54	67	60	80	105
4	200	700	1.46	29.22	51	68	57	72	100
4	200	800	1.47	29.15	55	70	62	73	100
3	200	200	1.25	29.22	58	72	68	88	130
3	200	300	1.17	29.22	56	70	66	83	121
3	200	400	1.25	29.14	52	66	62	87	115
3	200	500	1.10	29.14	50	63	59	82	108
3	200	600	1.25	29.08	54	67	57	81	105
3	200	700	1.23	29.22	51	68	57	72	100
3	200	800	1.12	29.15	55	72	61	73	100
2	200	200	0.81	29.22	57	73	69	87	131
2	200	300	0.80	29.22	56	70	66	83	121
2	200	400	0.87	29.14	52	65	61	86	115
2	200	500	0.85	29.14	51	63	58	82	108
2	200	600	0.84	29.08	54	67	60	82	105
2	200	700	0.83	29.22	51	68	57	72	100
2	200	800	0.81	29.15	55	74	59	72	100
1	200	200	0.41	29.22	57	72	67	85	128
1	200	300	0.42	29.22	57	72	65	82	120
1	200	400	0.43	29.14	52	64	58	85	113
1	200	500	0.41	29.14	52	64	57	82	107
1	200	600	0.42	29.08	54	68	58	82	104
1	200	700	0.41	29.22	51	68	56	71	100
1	200	800	0.39	29.15	55	74	59	72	100

Table 2 (Contd.). Experimental Data for Moisture Entrainment

Number of Banks	Water Pressure psig	Air Flow Cu.Ft/Min	Water Flow Cu.Ft/Min	Barometer In. Hg.	Air In t' °F	Air In t °F	Air After Spray °F	Air Out t' °F	Air Out t °F
4	300	200	1.72	29.15	58	72	72	90	131
4	300	300	1.71	29.15	58	72	72	88	124
4	300	400	1.70	29.10	54	65	67	85	116
4	300	500	1.74	29.10	55	68	65	82	111
4	300	600	1.75	29.10	56	70	64	79	108
4	300	700	1.73	29.35	48	62	57	71	99
3	300	200	1.38	29.15	58	72	73	90	131
3	300	300	1.46	29.15	58	72	72	89	125
3	300	400	1.35	29.10	54	65	66	85	116
3	300	500	1.32	29.10	55	68	65	82	111
3	300	600	1.34	29.10	56	70	64	78	108
3	300	700	1.34	29.35	48	62	56	70	98
2	300	200	0.98	29.15	58	72	73	90	130
2	300	300	0.98	29.15	58	72	72	88	125
2	300	400	1.00	29.10	54	65	65	84	115
2	300	500	1.00	29.10	54	67	64	81	113
2	300	600	0.98	29.10	56	70	62	78	107
2	300	700	1.00	29.35	48	63	55	70	98
1	300	200	0.49	29.15	58	72	72	89	130
1	300	300	0.49	29.15	58	72	70	87	124
1	300	400	0.55	29.10	54	66	63	83	115
1	300	500	0.49	29.10	54	66	62	81	111
1	300	600	0.49	29.10	56	70	62	77	107
1	300	700	0.48	29.35	54	70	57	71	100

Table 2 (Contd.). Experimental Data for Moisture Entrainment

Number of Banks	Water Pressure psig	Air Flow Cu.Ft/Min	Water Flow Cu.Ft/Min	Barometer In. Hg.	Air In t' °F	Air In t °F	Air After Spray °F	Air Out t' °F	Air Out t °F
4	400	200	1.95	29.08	52	64	71	90	129
4	400	300	2.05	29.08	52	64	67	85	120
4	400	400	1.98	29.08	52	64	65	81	115
4	400	500	1.99	29.08	52	64	63	79	110
4	400	600	1.97	29.08	52	65	64	78	107
4	400	700	2.01	29.35	55	74	63	75	105
3	400	200	1.54	29.08	52	64	71	89	128
3	400	300	1.53	29.08	52	64	67	85	121
3	400	400	1.54	29.08	52	64	65	81	115
3	400	500	1.53	29.08	52	64	63	78	109
3	400	600	1.52	29.10	56	73	67	80	110
3	400	700	1.55	29.35	55	74	63	75	105
2	400	200	1.13	29.08	52	64	70	89	130
2	400	300	1.14	29.08	52	64	66	85	121
2	400	400	1.15	29.08	52	64	64	81	115
2	400	500	1.09	29.08	52	64	62	78	109
2	400	600	1.14	29.10	57	72	65	80	110
2	400	700	1.15	29.35	55	72	62	74	103
1	400	200	0.56	29.08	52	64	67	87	129
1	400	300	0.56	29.08	52	64	64	84	121
1	400	400	0.57	29.08	52	64	62	80	114
1	400	500	0.55	29.08	52	64	60	77	108
1	400	600	0.56	29.10	56	72	64	78	109
1	400	700	0.56	29.35	54	72	59	72	102

Table 2 (Contd.). Experimental Data for Moisture Entrainment

Number of Banks	Water Pressure psig	Air Flow Cu.Ft/Min	Water Flow Cu.Ft/Min	Barometer In. Hg.	Air In t' °F	Air In t °F	Air After Spray °F	Air Out t' °F	Air Out t °F
4	500	200	2.19	29.08	52	64	73	92	131
4	500	300	2.22	29.10	50	63	70	88	122
4	500	400	2.22	29.10	50	62	68	85	116
4	500	500	2.19	29.10	50	64	64	80	111
4	500	600	2.20	29.26	54	72	65	76	106
4	500	700	2.17	29.26	54	74	63	75	105
3	500	200	1.70	29.08	52	64	73	91	129
3	500	300	1.74	29.10	50	63	70	88	122
3	500	400	1.71	29.10	50	63	67	84	116
3	500	500	1.70	29.10	50	64	65	80	110
3	500	600	1.70	29.26	54	73	65	76	107
3	500	700	1.70	29.26	54	74	63	75	105
2	500	200	1.25	29.08	51	63	72	91	130
2	500	300	1.29	29.10	50	63	69	87	122
2	500	400	1.25	29.10	50	64	65	83	115
2	500	500	1.29	29.10	50	64	64	80	111
2	500	600	1.27	29.26	53	72	64	76	107
2	500	700	1.25	29.15	54	70	61	74	103
1	500	200	0.62	29.08	51	71	71	90	130
1	500	300	0.63	29.10	51	66	66	86	121
1	500	400	0.62	29.10	50	63	63	82	115
1	500	500	0.63	29.10	50	62	62	79	110
1	500	600	0.63	29.26	53	62	62	75	106
1	500	700	0.64	29.26	53	61	61	74	104

Table 2 (Contd.). Experimental Data for Moisture Entrainment

Number of Banks	Water Pressure psig	Air Flow Cu.Ft/Min	Water Flow Cu.Ft/Min	Barometer In. Hg.	Air In t' °F	Air In t °F	Air After Spray °F	Air Out t' °F	Air Out t °F
4	600	200	2.37	29.20	58	75	76	89	133
4	600	300	2.37	29.20	57	77	77	88	129
4	600	400	2.37	29.20	58	77	75	85	122
4	600	500	2.36	29.20	58	77	73	83	117
4	600	600	2.35	29.20	58	77	71	81	113
4	600	700	2.37	29.20	58	77	70	79	109
3	600	200	1.88	29.20	60	73	78	90	135
3	600	300	1.88	29.20	60	73	74	85	125
3	600	400	1.87	29.20	60	74	78	85	122
3	600	500	1.88	29.20	60	74	71	82	117
3	600	600	1.88	29.20	60	74	70	80	112
3	600	700	1.87	29.20	56	75	68	78	108
2	600	200	1.23	29.20	60	73	80	90	135
2	600	300	1.23	29.20	60	73	79	88	128
2	600	400	1.23	29.20	60	73	77	86	124
2	600	500	1.28	29.20	60	73	75	85	119
2	600	600	1.26	29.20	60	73	72	81	113
2	600	700	1.32	29.20	60	73	70	80	109
1	600	200	0.65	29.20	60	73	79	89	135
1	600	300	0.72	29.20	58	71	73	85	126
1	600	400	0.72	29.20	57	70	69	81	118
1	600	500	0.70	29.20	57	70	68	80	114
1	600	600	0.71	29.20	56	70	67	78	110
1	600	700	0.67	29.20	57	70	66	77	106

Table 3. Experimental Results for Moisture Entrainment

100 psig

Banks	Air Flow Cu.Ft/Min	Air Flow Lb.Air/Min	Air In Lb.Water / Lb.Air	Air After Spray Lb.Water / Lb.Air	Air Out Lb.Water / Lb.Air	Carryover Grains Water	Entrainment Grains
4	200	14.57	.0049	.0123	.0163	1163	408
4	300	21.71	.0056	.0123	.0250	2940	1933
4	400	28.88	.0053	.0118	.0242	3810	2500
4	500	35.80	.0060	.0118	.0225	4070	2620
4	600	43.00	.0057	.0114	.0202	4260	2305
4	700	50.60	.0046	.0102	.0107	2130	177
4	800	56.80	.0052	.0118	.0113	2420	0
3	200	14.50	.0052	.0123	.0197	1417	753
3	300	21.67	.0055	.0123	.0225	2580	1550
3	400	28.88	.0053	.0114	.0254	4050	2850
3	500	35.80	.0061	.0118	.0224	4120	2660
3	600	43.00	.0057	.0110	.0202	4360	2774
3	700	50.70	.0048	.0098	.0109	2165	425
3	800	56.80	.0053	.0118	.0113	2420	0
2	200	14.55	.0052	.0123	.0228	1791	1070
2	300	21.80	.0034	.0118	.0225	2918	1632
2	400	28.80	.0022	.0114	.0252	4740	2780
2	500	35.85	.0058	.0123	.0224	4165	2540
2	600	43.00	.0059	.0106	.0194	4065	2645
2	700	50.80	.0049	.0098	.0101	1882	105
2	800	56.70	.0052	.0118	.0105	2100	0
1	200	14.55	.0052	.0123	.0219	1702	976
1	300	21.85	.0052	.0110	.0194	2177	1288
1	400	28.80	.0059	.0110	.0255	3945	2921
1	500	35.90	.0068	.0114	.0213	3640	2485
1	600	43.00	.0059	.0106	.0194	4060	2654
1	700	50.80	.0048	.0098	.0099	1603	35
1	800	56.70	.0052	.0122	.0105	2060	0

Table 3 (Contd.). Experimental Results for Moisture Entrainment

200 psig							
Banks	Air Flow Cu.Ft/Min	Air Flow Lb.Air/Min	Air In Lb.Water / Lb.Air	Air After Spray Lb.Water / Lb.Air	Air Out Lb.Water / Lb.Air	Carryover Grains Water	Entrain-ment Grains
4	200	14.32	.0073	.0156	.0200	1274	441
4	300	21.65	.0068	.0143	.0155	1302	167
4	400	28.91	.0058	.0122	.0222	3280	2025
4	500	36.40	.0071	.0114	.0184	2880	1780
4	600	43.70	.0062	.0114	.0171	3340	1743
4	700	51.71	.0043	.0102	.0118	2720	578
4	800	57.10	.0061	.0122	.0118	2281	0
3	200	14.39	.0074	.0154	.0203	1309	472
3	300	21.65	.0068	.0143	.0158	1365	227
3	400	29.10	.0053	.0122	.0226	3520	2120
3	500	36.60	.0049	.0112	.0195	3710	2125
3	600	43.00	.0062	.0105	.0163	3039	1750
3	700	50.50	.0043	.0104	.0113	2480	283
3	800	57.10	.0056	.0121	.0121	2600	0
2	200	14.29	.0068	.0156	.0187	1199	310
2	300	21.50	.0061	.0141	.0165	1570	361
2	400	28.90	.0055	.0119	.0221	3360	2065
2	500	36.26	.0054	.0106	.0189	3430	2110
2	600	45.95	.0062	.0114	.0192	4175	2510
2	700	50.90	.0043	.0102	.0109	2350	252
2	800	57.03	.0052	.0110	.0109	2365	0
1	200	14.35	.0068	.0146	.0168	981	221
1	300	21.50	.0068	.0136	.0154	1270	271
1	400	29.10	.0056	.0106	.0204	3020	1995
1	500	36.40	.0059	.0103	.0186	3265	2118
1	600	43.00	.0059	.0106	.0193	4040	2620
1	700	50.25	.0042	.0098	.0101	2070	156
1	800	57.03	.0043	.0110	.0101	2360	0

Table 3 (Contd.). Experimental Results for Moisture Entrainment

300 psig

Banks	Air Flow Cu.Ft/Min	Air Flow Lb.Air/Min	Air In Lb.Water/Lb.Air	Air After Spray Lb.Water/Lb.Air	Air Out Lb.Water/Lb.Air	Carryover Grains Water	Entrainment Grains
4	200	14.31	.0075	.0174	.0220	1455	462
4	300	21.50	.0075	.0174	.0214	2090	602
4	400	28.90	.0057	.0146	.0199	2970	1110
4	500	35.90	.0066	.0136	.0177	2780	1030
4	600	43.20	.0067	.0131	.0158	2743	820
4	700	51.60	.0041	.0102	.0101	2170	0
3	200	14.29	.0047	.0180	.0221	1735	406
3	300	21.42	.0074	.0174	.0224	2250	750
3	400	28.90	.0053	.0141	.0198	2930	1155
3	500	36.00	.0066	.0136	.0178	2820	1060
3	600	43.00	.0067	.0131	.0144	2318	392
3	700	50.60	.0041	.0098	.0095	1953	0
2	200	14.34	.0075	.0180	.0224	1505	431
2	300	21.50	.0075	.0175	.0212	2060	556
2	400	28.90	.0052	.0136	.0188	2750	1055
2	500	36.00	.0062	.0134	.0166	2620	1640
2	600	42.00	.0067	.0125	.0146	2380	633
2	700	51.40	.0038	.0094	.0096	2090	72
1	200	14.34	.0075	.0174	.0212	1388	384
1	300	21.50	.0075	.0163	.0202	1925	589
1	400	28.81	.0064	.0127	.0185	2440	1170
1	500	36.10	.0064	.0123	.0175	2800	1314
1	600	43.00	.0066	.0122	.0137	2140	452
1	700	50.20	.0064	.0101	.0100	1270	0

Table 3 (Contd.). Experimental Results for Moisture Entrainment

400 psig

Banks	Air Flow Cu.Ft/Min	Air Flow Lb.Air/Min	Air In Lb.Water/Lb.Air	Air After Spray Lb.Water/Lb.Air	Air Out Lb.Water/Lb.Air	Carryover Grains Water	Entrainment Grains
4	200	14.54	.0058	.0169	.0227	1730	589
4	300	21.80	.0058	.0147	.0188	1980	625
4	400	29.10	.0058	.0136	.0158	2035	448
4	500	36.35	.0058	.0128	.0148	2280	508
4	600	43.40	.0055	.0132	.0146	2755	425
4	700	49.99	.0051	.0126	.0122	2480	0
3	200	14.54	.0058	.0169	.0217	1620	498
3	300	21.80	.0058	.0147	.0186	1950	595
3	400	29.10	.0058	.0136	.0158	2035	427
3	500	36.35	.0058	.0128	.0141	2170	356
3	600	43.51	.0059	.0146	.0159	3041	396
3	700	50.80	.0050	.0126	.0122	2490	0
2	200	14.54	.0058	.0163	.0212	1570	498
2	300	21.80	.0058	.0141	.0186	1950	686
2	400	29.10	.0058	.0132	.0157	2035	508
2	500	36.35	.0058	.0123	.0143	2190	510
2	600	42.80	.0068	.0137	.0159	2730	660
2	700	50.60	.0046	.0122	.0116	2480	0
1	200	14.54	.0058	.0147	.0190	1345	438
1	300	21.80	.0058	.0132	.0166	1650	520
1	400	29.10	.0058	.0123	.0150	1878	549
1	500	36.35	.0058	.0114	.0135	1930	505
1	600	42.60	.0062	.0132	.0143	2420	329
1	700	50.65	.0040	.0109	.0104	2240	0

Table 3 (Contd.). Experimental Results for Moisture Entrainment

500 psig

Banks	Air Flow Cu.Ft/Min	Air Flow Lb.Air/Min	Air In Lb.Water / Lb.Air	Air After Spray Lb.Water / Lb.Air	Air Out Lb.Water / Lb.Air	Carryover Grains Water	Entrain-ment Grains
4	200	14.55	.0058	.0181	.0249	1950	693
4	300	21.82	.0049	.0163	.0212	2490	904
4	400	29.16	.0051	.0152	.0198	3000	940
4	500	36.32	.0046	.0132	.0157	2800	637
4	600	43.25	.0050	.0136	.0129	2390	0
4	700	50.22	.0046	.0126	.0123	2700	0
3	200	14.55	.0058	.0181	.0240	1850	600
3	300	21.82	.0049	.0163	.0212	2490	900
3	400	29.10	.0049	.0146	.0186	2790	817
3	500	36.32	.0047	.0132	.0160	2870	715
3	600	43.00	.0048	.0136	.0126	2350	0
3	700	50.20	.0046	.0126	.0123	2880	0
2	200	14.53	.0055	.0175	.0239	1875	700
2	300	21.85	.0049	.0157	.0208	2440	781
2	400	29.10	.0047	.0136	.0177	2645	835
2	500	36.40	.0047	.0132	.0157	2800	637
2	600	43.00	.0044	.0131	.0126	2464	0
2	700	50.20	.0055	.0119	.0119	2250	0
1	200	14.53	.0055	.0169	.0223	1710	550
1	300	21.80	.0052	.0142	.0197	2210	840
1	400	29.10	.0047	.0127	.0168	2460	835
1	500	36.50	.0047	.0122	.0150	2635	716
1	600	43.05	.0042	.0122	.0120	2350	0
1	700	50.15	.0042	.0117	.0116	2590	0

Table 3 (Contd.). Experimental Results for Moisture Entrainment

600 psig

Banks	Air Flow Cu.Ft/Min	Air Flow Lb.Air/Min	Air In Lb.Water/Lb.Air	Air After Spray Lb.Water/Lb.Air	Air Out Lb.Water/Lb.Air	Carryover Grains Water	Entrainment Grains
4	200	14.21	.0062	.0201	.0201	1386	0
4	300	21.20	.0056	.0208	.0208	2250	0
4	400	28.30	.0063	.0193	.0174	2200	0
4	500	25.40	.0063	.0180	.0173	2730	0
4	600	42.40	.0063	.0168	.0161	2900	0
4	700	49.50	.0063	.0163	.0150	3010	0
3	200	14.21	.0084	.0213	.0213	1290	0
3	300	21.34	.0084	.0186	.0178	1470	0
3	400	28.45	.0082	.0213	.0174	1830	0
3	500	35.60	.0082	.0168	.0162	1980	0
3	600	42.58	.0085	.0163	.0154	2060	0
3	700	49.75	.0055	.0651	.0143	3068	0
2	200	14.24	.0083	.0229	.0210	1270	0
2	300	21.41	.0083	.0221	.0203	1805	0
2	400	28.45	.0083	.0207	.0188	2090	0
2	500	35.60	.0083	.0193	.0190	2670	0
2	600	42.60	.0083	.0174	.0161	2320	0
2	700	49.89	.0083	.0163	.0160	2690	0
1	200	14.24	.0083	.0221	.0200	1170	0
1	300	21.45	.0076	.0179	.0173	1470	0
1	400	28.70	.0072	.0156	.0150	1545	0
1	500	39.81	.0072	.0151	.0149	2250	0
1	600	43.00	.0066	.0146	.0138	2170	0
1	700	50.20	.0073	.0141	.0139	2320	0

APPENDIX C

GLOSSARY AND SAMPLE CALCULATIONS

Glossary

Nozzle Bank	--	Six spray nozzles equally spaced around the periphery of the fog-clone in a common horizontal plane.
Spray Pressure	--	The water pressure from the high pressure pump on the nozzle banks.
Fog-clone	--	Name given to the fog-type dust collector for this test.
Carryover	--	Actual quantity of moisture increases in air as it passes through the fog-clone.
Entrainment	--	Actual quantity of moisture above saturation temperature of leaving air.
t	--	Dry bulb temperature.
t'	--	Wet bulb temperature.

Sample Calculations

1. Given the following experimental data for moisture entrainment (see Table 2):

No. of Banks	Water Pressure psig	Air Flow Cu.Ft/Min	Water Flow Cu.Ft/Min	Barometer In. Hg.	Air In t' °F	Air In t °F	Air After Spray °F	Air Out t' °F	Air Out t °F
4	300	500	1.74	29.10	55	68	65	82	111

2. Find the number of grains carryover and the number of grains entrainment.

3. Solution:

Using the following equations[9]:

1. $$W' = 0.625 \left(\frac{P_w}{P - P_w}\right)$$

where:

W' = weight of moisture in one pound of dry air if saturated at the wet bulb temperature t'

0.625 = specific weight of water vapor

P_w = pressure of saturated water vapor at t'

P = barometric pressure.

2. $$W = \frac{W'h_{fg'} - 0.24(t - t')}{h_{fg'} + 0.45(t - t')}$$

where:

$$W' = 0.625\left(\frac{P_w}{P - P_w}\right)$$

$h_{fg'}$ = latent heat of water vapor at temperature t' (°F)

0.45 = specific heat of water vapor (BTU/lb./°F)

0.24 = specific heat of air (BTU/lb./°F)

t - t' = wet bulb depression (°F)

P_w = saturated vapor pressure corresponding to the temperature t'.

Using the following t's and referring to the Thermodynamic Properties of Steam by Keenan and Keys[10]:

1. Air In $t' = 55°F$, $P_w = 0.436$, $h_{fg'} = 1062$
2. Air After Spray $t' = 65°F$, $P_w = 0.622$, $h_{fg'} = 1057$
3. Air Out $t' = 82°F$, $P_w = 1.102$, $h_{fg'} = 1047$

1. $$W' = 0.625\left(\frac{0.436}{29.10 - 0.436}\right) = 0.0095$$

2. $$W' = 0.625\left(\frac{0.622}{29.10 - 0.622}\right) = 0.0136$$

3. $$W' = 0.625\left(\frac{1.102}{29.10 - 1.102}\right) = 0.0246$$

1. $$W = \frac{(0.0095)(1062) - 0.24(13)}{(1062) + 0.45(13)}$$

$$W = 0.0066\ \frac{\text{lb. moisture}}{\text{lb. air}}$$

2. $$W = \frac{(0.0136)(1057) - 0.24(0)}{1057 + 0.45(0)}$$

$$W = 0.0136 \frac{\text{lb. moisture}}{\text{lb. air}}$$

3. $$W = \frac{(0.0246)(1047) - 0.24(29)}{1047 + 0.45(29)}$$

Now taking entrance conditions to calculate the specific volume of air by the orifice. Using the relation

$$\frac{V}{W} = \frac{RT}{70.6(P - P_W)}$$

where

$\frac{V}{W}$ = specific volume of air cu. ft/lb.

R = gas constant 53.3

T = absolute temperature air in

P = barometric pressure

P_W = pressure of saturated water vapor at t'

70.6 = 144(.491) to obtain proper units.

$$V = \frac{53.3(460 + 68)}{70.6(29.10 - 0.436)} = 13.91 \text{ cu. ft/lb.}$$

$$\frac{500 \text{ cu. ft/min}}{13.91 \text{ cu. ft/lb.}} = 39.90 \text{ lb. air/min}$$

$$\text{Carryover} = \text{Air Out } \left(\frac{\text{lb. Moisture}}{\text{lb. Air}}\right) - \text{Air In } \left(\frac{\text{lb. Moisture}}{\text{lb. Air}}\right)$$

$$= 0.0177 - 0.0066 = 0.0111 \left(\frac{\text{lb. Moisture}}{\text{lb. Air}}\right)$$

$$\text{Entrainment} = \text{Air Out} \left(\frac{\text{lb. Moisture}}{\text{lb. Air}}\right) - \text{Air After Spray} \left(\frac{\text{lb. Moisture}}{\text{lb. Air}}\right)$$

$$= 0.0177 - 0.0136 = 0.0041 \left(\frac{\text{lb. Moisture}}{\text{lb. Air}}\right)$$

$$\text{Carryover in grains} = 0.111 \left(\frac{\text{lb. Moisture}}{\text{lb. Air}}\right) \times 39.90 \left(\frac{\text{lb. Air}}{\text{Min}}\right) \times 7000$$

where

one pound water = 7000 grains

$$= 2780 \text{ grains/min}$$

$$\text{Entrainment} = 0.0041 \left(\frac{\text{lb. Moisture}}{\text{lb. Air}}\right) \times 39.90 \left(\frac{\text{lb. Air}}{\text{Min}}\right) \times 7000$$

$$= 1030 \text{ grains/min.}$$

BIBLIOGRAPHY

1. Hudson, D. G., The Principal of the Fog Filter, Unpublished paper presented at the Tenth Annual Meeting of the American Industrial Hygiene Association, 1949.

2. Kernan, C. R., Jr., "Efficiency of the Fog-Type Dust Collector at Low Dust Loadings," M.S. Thesis, Georgia Institute of Technology, School of Mechanical Engineering, 1952, 39 pp.

3. Thomas, F. A., Jr., "Effectiveness of the Fog Filter," Heating and Ventilating, Vol. 50, No. 2, February 1953, p 113.

4. Krapp, E. P. and R. N. Simonsen, "How Sohio Fights Air Pollution," The Oil and Gas Journal, Vol. 51, No. 11, July 21, 1952, p 85.

5. Thomas, F. A. Jr., "A Study of the Flow of Air into Plane Obstructed Openings," M.S. Thesis, Georgia Institute of Technology, School of Mechanical Engineering, 1949, p 51.

6. American Society of Mechanical Engineers, Flow Measurement, Part 5, Chapter 4, New York: The American Society of Mechanical Engineers, 1949, 64 pp.

7. ASME, op. cit., 64 pp.

8. Siegel, L. G., "Psychrometric Instrumentation," Heating, Piping and Air Conditioning, ASHVE Journal Section, Vol. 18, No. 10, October 1946, p 101.

9. Carrier, W. H., Cherne, R. E. and W. A. Grant, Modern Air-Conditioning, Heating, and Ventilating, Pitman Publishing Corporation, New York, 1940, p 15.

10. Keenan, J. H. and F. G. Keyes, Thermodynamic Properties of Steam, John Wiley and Sons, Inc., New York, 1936, 89 pp.